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# Satellite Survival in CDM Cosmology

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## ABSTRACT

We study the survival of sub-structures (clumps) within larger self-gravitating dark matter haloes. Building on scaling relations obtained from $N$-body calculations of violent relaxation, we argue that the tidal field of galaxies and haloes can only destroy sub-structures if spherical symmetry is imposed at formation. We explore other mechanisms that may tailor the number of halo sub-structures during the course of virialisation. Unless the larger halo is built up from a few large clumps, we find that clump-clump encounters are unlikely to homogenise the halo on a dynamical timescale. Phase-mixing would proceed faster in the inner parts and allow for the secular evolution of a stellar disc.

## 1. Introduction

High-resolution simulations of structure formation in an ΛCDM cosmogony have revealed a large number of substructures within dark matter haloes (e.g. Ghigna et al. 2000; Moore 2001). The mass function of these dark clumps (Moore et al. 1999a; de Lucia et al. 2004)

$$n(m) \propto m^{-2} \tag{1}$$

in the mass range $10^8$ to $10^{11}$ solar masses. These orbiting self-bound dark matter satellites would drag along baryonic matter to a non-negligible fraction of their mass. Consequently galaxies should harbour a large number of dwarf galaxies, when only a handful are found (Kauffmann et al. 1993; Moore et al. 1999a; see Binney & Merryfield 1999).

The situation is made worse from a dynamical standpoint. Massive dark clumps would perturb the vertical structure of galactic discs through tidal heating, when their thin structure suggests the immediate neighbourhood of discs is devoid of such perturbations (Toth & Ostriker 1992; Moore et al. 1999a). **The large-mass end of the clump mass distribution function is robust in view of Simulation checks find the large-mass end of the clump mass distribution function robust to numerical resolution issues (Moore et al. 1999b; Gao et al. 2004; Power et al. 2003).** Therefore, the orbital distribution of clumps in phase space must allow for **long periods of unperturbed evolution** by the disc, as emphasised by Navarro (2002) and Font et al. (2003). A more severe problem is the narrowness of streams of stars associated with dwarf

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galaxies tidal debris (Ibata et al. 2001; Johnston et al. 2001), which suggests a smooth background halo potential in order to preserve the cohesion of the stream, in direct conflict with computer simulations of structure formation. **Observational evidence drawn from solar neighbourhood kinematics points to a fine-meshing of low-mass streams to account for coherent motion in and out of the galactic plane (Helmi et al. 2002; Gould 2003).** To settle this issue requires **both a precise map of the morphology of haloes and** convergence in the mass distribution function of clumps with a resolution down to **the sub-dwarf mass range**, still a challenge to present-day computer models (see e.g. Power et al. 2003). **The morphology of haloes has been discussed at length by several authors (e.g., Moore 2001; Ghigna et al. 2000; Fukushige & Makino 2003; Power et al. 2003; Navarro et al. 2004). Several contributions in Natarajan (2002) give a broad overview of the formation processes and equilibrium properties of haloes derived from numerical simulations and possible observational tests for their detection.**

Particle-based calculations of galaxy formation proceed with a number routinely approaching a few $\times 10^7$ particles for a whole simulation. The mass of individual particles that make up dark haloes in these simulations $\simeq 10^6 M_\odot$ is still large compared with a mass spectrum of dark matter that may yet include a population of brown dwarfs (i.e., stellar masses). **Furthermore, of order $\sim 10^5$ mass elements must participate in the formation of a self-gravitating body to resolve the growth of potential energy adequately (Boily et al. 2002; Roy & Perez 2004), or a mass resolution of $10^8/10^5 \simeq 10^3\,\mathrm{M}_\odot$ to account for dwarf-size structures.** This leaves a gap in mass resolution of some three orders of magnitude with that achieved by present-day simulations. In this context, we need establish when the statistics of dark matter clumps derived from N-body computations may be scaled up to **actual** galactic systems. A crude picture of halo formation divides the process in two stages: one of rapid collapse on a free-fall time scale, followed by a second, longer period of sporadic accretion (Bower 1991; Lacey & Cole 1994; Zhao et al. 2003a,b). **The first stage involves structures spread over a narrow range of masses, while the second stage sees low-rate accretion by a dominating, central body.** The growth of potential energy during the free-fall stage of formation sets the maximum phase-space density of the distribution function by efficiently, if incompletely, redistributing binding energy between particles **(Lynden-Bell 1967; van Albada 1982)**.

The growth of potential energy during collapse of self-gravitating systems is a function of the initial morphology and the number of particles (or quivalently, mass resolution) used in the computation (e.g. Boily et al. 2002 **and references therein**). A direct consequence of this is that the maximum tidal field $\propto \nabla^2\phi(r)$ experienced by galactic satellites **(dark or baryonic) as they fly through the system** varies with the morphology of the underlying halo, i.e., its formation history. For instance, at fixed resolution, the strength of tidal fields reaches a higher maximum for an initially spherical distribution than for an axi-symmetric or triaxial one. The simplification of symmetric distributions allows to scale up the results with particle number exactly (see §2 below). Would the tidal heating experienced by dark clumps during infall, scaled up to actual galactic halo particle numbers, be sufficient to unbind them? In this short contribution, we apply the results **violent relaxation studies** to the tidal heating of galactic substructures in a hierarchical Einstein-deSitter universe. We show that the tidal field developing during infall may yet be sufficient to erase sub-structures smaller than a critical linear size $l_c$ if the particle number $N$ is sufficiently large *and* the galactic halo shows axial- or spherical symmetry during infall.

## 2. Scaling of tidal fields

Aarseth, Lin and Papaloizou (1988) (hereafter ALP+88) have shown that the growth rate of global modes of fragmentation during violent relaxation is such that the minimal radius achieved by a spherical distribution scales with the simulation particle number $N$ as

$$\mathcal{C} \equiv \frac{R(0)}{R(t_{\rm ff})} \propto N^{1/3} \qquad (2)$$

where $R(0)$ is the initial system size enclosing $N$ identical mass elements and $R(t_{\rm ff})$ the radial size at the free-fall time $t_{\rm ff}$ defined by

$$t_{\rm ff} = \sqrt{\frac{3\pi}{32G <\rho(a,0)>}} \tag{3}$$

where $<\rho(a,0)>= 4\pi M/3a^3$ is the mean density inside the particle's initial radius, $a$. A recent study extended the result (2) empirically with N-body calculations to axisymmetric (cylindrical) and triaxial initial configurations (Boily et al. 2002). It was found in these cases that $\mathcal{C}$ scales with particle number as

$$\mathcal{C} \propto \begin{cases} N^{1/6} & \text{(axisymmetry)} \\ \text{constant} & \text{(triaxial).} \end{cases} \tag{4}$$

The factor $\mathcal{C}$ achieved by systems starting from triaxial distributions remains $\lesssim 40$ for $\simeq 86\%$ of the parameter space of axial ratios $a:b:c$, however the maximum achieved by individual realisations is highly sensitive to the initial axes ratios and may yet diverge. N-body simulations using direct-integration algorithms (ALP+88; Theis & Spurzem 1999; Boily, Clarke & Murray 1999) or FFT integrators (e.g., Boily et al. 2002) reproduce these relations over several decades in particle number, giving confidence that the results are well recovered independently of the numerical method used. A consequence of (2) and (4) is that a spherical or axisymmetric distribution will contract ever more as the number N of particles is increased. The morphological evolution of haloes and their substructures will not be well resolved if at formation the particle number which take part in the relaxation phase is too low. Zhao et al. (2003a,b) show that the formation history runs through a rapid accretion phase, followed by slow growth of the outer halo. The scaling law (2) and (4) obtained for violent relaxation would therefore apply best to the first, early phase of formation, but not the late one.

## 3. Cosmological application

The mean tidal field of a collapsing halo is evaluated from the time-dependent second derivative of the gravitational potential

$$F_t = l_c \times \nabla^2\Phi\big|_R = -l_c \frac{GM}{R^3} \tag{5}$$

with $r <$ the system radius $R$, and double-differencing with respect to $r$ at fixed time yields a measure of the tidal field at $R$ acting on a clump of size $l_c$. It is clear that the tidal force is unbound if during collapse $R(t_{\rm ff}) \to 0$, as would occur e.g. for a large-N spherical distribution, cf. (2).

Bound clumps would survive violent relaxation if their binding energy is higher than the tidal heating they suffer during that phase (van Albada 1982; Tsuchiya 1998). As shown from (5), remnant structures will be severely disrupted if the maximal potential depth achieved is large. To progress further we need invoke a result for structure formation in an expanding Universe. Present-day data support an asymptotically flat metric for the Universe, and hence the Einstein-deSitter cosmogony remains attractive.

### 3.1. Background tidal heating

In an EdS universe the relation between a bound structure's mass and virial radius is (Kaiser 1986; Padmanabhan 1993; Somerville & Primack 1999)

$$R \propto M^\gamma \tag{6}$$

with $\gamma$ known in terms of the power-spectrum of density fluctuations $P(\boldsymbol{k})$ at wavenumber $\boldsymbol{k}$. The classic CDM power spectrum at the time $\tau$ of galaxy formation accounts for the time-evolution of structure from a bottom-up point of view. The relation between $P(\boldsymbol{k};\tau)$ and the Zeldovich spectrum arising from post-inflation decoupling, $P(\boldsymbol{k};t_i)$, is (see Bardeen et al. 1986, Appendix G):

$$P(\boldsymbol{k};\tau) = \left[\frac{a(t_i)}{a(t)}\right]^2 T^2(\boldsymbol{k})P(\boldsymbol{k};t_i) \tag{7}$$

where $a$ is the cosmical expansion factor and $T$ the tranfer function which is well approximated analytically by

$$T(q) = \frac{\ln(1+2.34q)}{2.34q}\left(1+3.9q+259q^2+163q^3+2027q^4\right)^{-\dfrac{1}{4}} \tag{8}$$

with $q \equiv |k|\sqrt{\theta}/(\Omega h^2 {\rm Mpc}^{-1})$, $\theta = \rho_{rel}/1.68\rho_\gamma$ is the ratio of relativistic paticles to photon energy densities. On the largest scales the Zeldovich spectrum $P(\boldsymbol{k};\tau) \propto P(\boldsymbol{k};t_i) \propto k$ is recovered from (8),

while on small scales $P(\boldsymbol{k};\tau) \propto k^{-3}$. If we fit the power spectrum locally to a power-law of index $n_k$, $P(\boldsymbol{k}) \propto k^{n_k}$, the index shifts progressively from $n_k = +1$ to $n_k = -3$ as we explore smaller scales. The indices $n_k$ and $\gamma$ are linked through the mass-radius relation (6)

$$\gamma = (n_k + 5)/6\,.$$

Note that $\gamma$ is related to the power-index $\nu$ relating mean density and mass, $\rho \propto M^{\nu}$, by $\nu = \gamma - 3 = (n_k - 13)/6$; the free-fall time $t_{\rm ff} \propto 1/\sqrt{\rho}$ therefore scales with mass as

$$t_{\rm ff} \propto M^{(13-n_k)/12}.$$

On the smallest scales $n_k \to -3$ and $t_{\rm ff} \propto M^{4/3}$, a steeper relation than on the largest scales when $n_k \to +1$ and $t_{\rm ff} \propto M$. Therefore small clumps have fully virialised when the violent relaxation phase of the larger halo begins.

Since there is no fixed scales of mass or radius in gravitational dynamics, all virialised structures obey the same relation (6). If we lump together all those of virial radius $< r$, of mass $m$ chosen such that $M/m = N \gg 1$, we have

$$\frac{R}{r} \propto \left(\frac{M}{m}\right)^{\gamma} = N^{(n_k+5)/6}\ . \tag{9}$$

In a hierarchical universe, small structures form first and hence the $N$ small clumps have virialised well before the large underlying halo, of total mass $M$. At constant mass the virial theorem provides a relation between equilibrium radius an initial size $R_i$ for a self-gravitating system:

$$R_i = 2R \tag{10}$$

which applies equally to all structures. We need relate the tidal field (5) with (2) and (4) to determine whether a structure of size $r_i$ survives the formation of the larger halo, of radius $R_i$. The energy transferred to a small clump by tidal forces during infall is adequately quantified by Spitzer's (1958) impulse approximation formula even for relatively slow encounters (Aguilar & White 1985). This gives confidence that it will hold in the present context, where velocities are high. Tsuchiya (1998) finds this to be correct in his study of relaxing Plummer distributions. The tidal energy gained $\Delta E$ by a substructure of mass $m$, radius $r$, and internal binding energy $E$ may be evaluated for a single passage at velocity $V$ across the background halo (or galaxy) potential at the time of collapse, when the tide is maximum. In the impulse approximation, this is given by

$$\Delta E = \frac{4G^2M^2m}{3R(t_{\rm ff})^4V^2}\,\bar{r}^2 \approx \left(\frac{\bar{r}}{R_i}\right)^3 \mathcal{C}^3\,\frac{M}{m}\,E\,. \tag{11}$$

Note that (11) applies to the tidal field of the background potential, and does not account for individual clump encounters. These are discussed later. Substituting (9) in (11) we get

$$\Delta E = N^{-(n_k+3)/2}\left(\frac{\mathcal{C}}{2}\right)^3 E \tag{12}$$

whence we deduce that $\Delta E \ll E$ if the coefficient $N^{-(n_k+3)/2}\mathcal{C}^3$ remains small. For spherical systems the collapse factor $\mathcal{C}$ obeys (2) and therefore

$$\frac{\Delta E}{E} \propto N^{-(n_k+1)/2} \qquad \text{(spherical distributions)}$$

while for axisymmetric or triaxial distributions we find from (4)

$$\frac{\Delta E}{E} \propto \begin{cases} N^{-(n_k+2)/2} & \text{(spheroidal)} \\ N^{-(n_k+3)/2} & \text{(triaxial).} \end{cases} \tag{13}$$

The consequences of these results in relation to the power-spectrum of density fluctuations is clear: for clumps orbiting in a collapsing spherical halo or galaxy, tidal heating will be ineffective provided $n_k > -1$. If the underlying distribution is axisymmetric, tidal heating will be ineffective when $n_k > -2$. However for triaxial initial conditions this will hold true if $n_k > -3$. Since the power-spectrum of observed matter distribution is never steeper than $n_k = -3$, we deduce that the bulk of substructures or clumps evolving in larger structures, such as dark matter haloes, will survive the formation of triaxial larger structures, if gravity alone fixes their binding energy.

### 3.2. Tidal heating due to other substructures

The above conclusion only concerns the response of clumps to the background tidal field.

We may consider the interaction between clumps themselves as they cross the dense system. To this end we consider the tidal heating by two equal-mass substructures during an encounter. Substituting $M \to m$ in (11) and the radius $R(t_{\rm ff})$ by the mean distance between clumps $x \approx R(t_{\rm ff})/N^{1/3}$, an effective impact parameter, we find

$$\Delta E = \frac{4G^2m^3}{3(R/N^{1/3})^4V^2}\,\bar{r}^2 \approx \frac{2}{3}\frac{m}{M}N^{4/3}\left(\frac{\bar{r}}{R}\right)^3 \; E\,.$$

In the above we used $V^2 \approx 2GM/R$, with $M = Nm$ the total system mass as before. The expression reduces to

$$\Delta E \approx \frac{2}{3}N^{1/3}\left(\frac{\bar{r}}{R}\right)^3 \; E\,. \qquad (14)$$

Clearly to achieve $\Delta E \approx E$ requires $r \sim R$ or $N \gg 1$. we may simplify (14) by substituting for $\bar{r}$ using (9). We then find

$$\Delta E < \frac{2}{3}N^{-(13+3n_k)/6}\; E\,. \qquad (15)$$

Thus for any appreciable number $N$ the tidal heating due to encounters between clumps will be significant if $n_k < -13/3 = -4\frac{1}{3}$. No regime of the power spectrum covers that range and hence encounters between clumps never produce significant tidal heating. **A direct consequence of this is that while haloes form at different redshifts and sample different regimes of the structure power-spectrum, the mass distribution function of substructures should be robust against cut-offs or significant changes to its shape. It is not clear yet whether the scale-free nature of the clump mass function (1) measured in N-body simulations (e.g. Ghigna et al 2000) can be extended to very small masses (see Gao et al. 2004).**

There is of course one situation when substructures can heat-up one another through tidal forces, which is when $\bar{r} \sim R(0)$ or $R(t_{\rm ff})$ and $N \sim 1$. Indeed when $\bar{r}$ matches the mean inter-clump distance $\approx R(t_{\rm ff})/N^{1/3}$, we compute $\Delta E/E \sim 1$, always. However this situation is more appropriate to galactic mergers than the formation of halo through accretion of several sub-units, as would occur in any bottom-up calculation of galaxy formation.

The survival of substructures is in part due to the large relative velocity $V$ established under the mutual potential of all clumps. Survival during infall is no guarantee that the substructures would remain once the halo has achieved virial equilibrium. To estimate more precisely the net rate of heating on one clump due to the background tidal field as it crosses the system is made difficult because of the large changes in potential taking place during violent relaxation. This is best done with numerical N-body calculations tailored for this problem. The very high-resolution simulations performed by e.g. Ghigna et al. (2000) demonstrate the likely survival of most substructures in and around dark matter haloes post-virialisation, in support of the basic argument outlined here.

## 4. Discussion and conclusion

Galactic satellites survive the formation phase of triaxial haloes and galaxies and will be destroyed on long timescales as they orbit the host galaxy. This result is obtained both from large N-body simulations (see also e.g. Bullock et al. 2000; Ghigna et al. 2000) and from **semi-analytic arguments (Moore et al. 1996; Taffoni et al. 2003)** as well as the fluid calculation presented here, and is therefore robust. The initial conditions and subsequent evolution of N-body computer simulations still plague their interpretation and application to observed galaxies in terms of simple estimates of satellite disruption times. For instance, Font et al. (2003) and Ardi et al. (2002) have questioned the rate of disc heating by in-falling dark satellites. These authors find that thin discs may yet remain stable despite a high count of bound dark matter clumps, provided the clumps do not follow near-radial orbits. The problem of disc heating would seemingly not occur if the inner region of the halo were isotropic in phase-space. We already noted that the destruction of dark satellites would be more effective in the deep potential of the inner halo. **Recently Gao et al. (2004) have rederived statistics of halo substructures in computer simulations and found them to be less concentrated than the host halo. This and the coherence of cold-stream satellite debris cold-stream debris could be interpreted in the light of the present analysis as pointing to a near-spherical (and hence**

**destructive), early phase of halo formation. Several studies have argued for a more spherical morphology in the inner region of haloes (e.g., Blumenthal et al. 1986; Dubinsky 1994). The cooling of baryons at the heart of DM haloes would provide a mechanism for this by locking the inner halo morphology to a rounder shape than obtained from strictly gravitational evolution (Dubinsky 1994; Frenk et al. 1996). The inner morphology of galactic haloes would not automatically be spherical if baryons have had time to cool and form discs *before* the halo assembly is comlete : when that is the case, the halo's inner morphology in equilibrium is even more sensitive to the formation history and depends for instance on the orientation of the discs as they merge (see Kazantzidis et al. 2004)**

Possible mechanisms that may disrupt dark clumps on the dwarf galaxy mass-scale and below include supernova blow outs through gas irradiation and expulsion (Efstathiou 1992; Somerville 2002; Gnedin & Zhao 2002). The net effect of gas loss on gravitationally bound structures is unlikely to be effective if the gas mass fraction is small (Hills 1980; Boily & Kroupa 2002). Gnedin & Zhao (2002) have argued that the peaked density profiles obtained from CDM numerical calculations would resist rapid removal of the gas under any realistic circumstances. Thus unless the **dwarf-size** clumps contain a very large fraction of baryonic matter they will survive any degree of gas heating. Côté et al. (2002) presented a Monte Carlo simulation of chemical enrichment of galaxies through gas-evaporation from clumps of dark matter initially seeded with baryons (uniform M/L ratio). They find that the mass function of seeded clumps required to match their sample of galaxies (in terms of chemical gradients and observable dwarf galaxy and star cluster populations) is similar to the mass function (1) obtained from large-N cosmological calculations. This would suggest that the high-mass end of the clump mass function survives the formation of the host dark halo to produce the observed population of dwarfs. It does not however suppress the number of dark clumps that may still be orbiting the halo. Another route to solving the over-abundance of dwarf galaxies is by **preventing (bright) baryons from forming stars**. This can be achieved either through background UV radiation (Efstathiou 1992; Somerville 2002), or by preventing a Toomre instability from developing fully (Verde et al. 2002), effectively shutting off the formation of stars in the first place. **Gas-rich dwarfs would undergo substantial morphological evolution through ram stripping from the IGM ; their long-term fate (destruction or survival) must account for such evolution since it will change the dwarf binding energy through dissipation (Mayer et al. 2001).**

Dynamical friction can in principle provide an alternative solution if the clumps spiral in rapidly and lose mass owing to tidal heating (Syer & White 1998; Tormen et al. 1998). Computer simulations and analysis of decaying satellites show that a heavy satellite loses up to 90% of its mass in a few orbital periods (e.g. Klessen & Kroupa 1998; Peñarrubia et al. 2002; Taffoni et al. 2003; see also Hashimoto et al. 2003). van Kampen (2002) has argued that the effect of dynamical friction may yet be underestimated in computer simulations due to limited mass resolution. Dynamical friction, in conjunction with tidal forces, will cause the disruption of a satellite after a period of time (e.g. Ibata et al. 1994; Klessen & Kroupa 1998; Bullock et al. 2001). Bullock et al. (2001) argue that the halo stellar population of the Milky Way may be accounted for if sufficient satellite dwarf galaxies had already accreted their mass at the time the galactic halo formed and are then stripped of their less-bound stars by galactic tides. Clearly the link between halo morphology, halo sub-structure statistics and stellar populations offers more avenues for future work.

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